

A Collection of Amp Applications

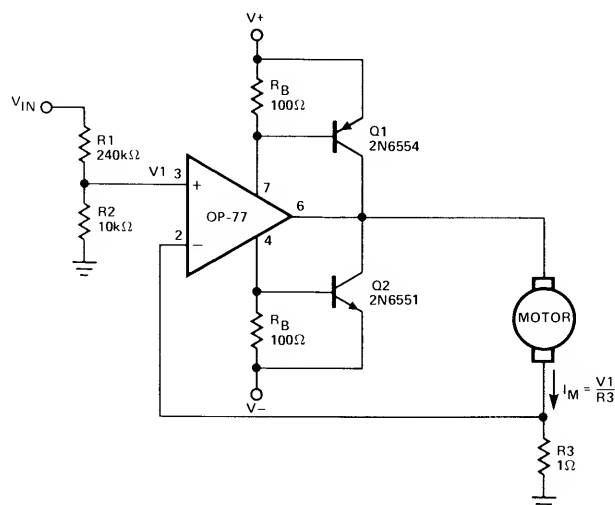
by James Wong

This note examines some of the numerous and widely-used applications of the operational amplifier. While not attempting to list every possible application, it presents several basic circuit configurations that can be modified to suit applications other than those listed. In each case, significant op amp or circuit characteristics are discussed to aid the user in adapting the circuit to a particular need. Table 1 provides an index to the applications contained in this note.

TABLE 1: Op Amp Circuit Applications

Figure	Application
1	±200mA Servo Motor Amplifier
2	Precision Programmable Gain Amplifier
3	Bilateral Current Source
4	Precision Current Pump
5	High-Sensitivity Voltage Comparator
6	Micropower 5V Regulator
7	Micropower 1.23V Bandgap Reference
8	Versatile Triangular Wave Generator
9	Wide Range, Low Current Ammeter
10	Precision Threshold Detector/Amplifier
11	Wide-Dynamic-Range Light Detector
12	Isolation Amplifier
13	Dual Programmable Window Comparator
14	±36V Low Noise Operational Amplifier
15	High Q Notch Filter
16	Piezoelectric Transducer Amplifier
17	High Stability Voltage Reference
18	Precision Dual Tracking Voltage Reference
19	RIAA Phono Pre-Amplifier
20	Headphone Amplifier
21	NAB Tape Head Pre-Amplifier
22	Microphone Pre-Amplifier
23	Micropower Wien Bridge Oscillator
24	Micropower Instrumentation Amplifier
25	Piecewise-Linear Amplifier (Decreasing Gain)
26	Piecewise-Linear Amplifier (Increasing Gain)
27	Current Monitor Circuit
28	Free-Running Square-Wave Oscillator
29	Precision Analog Multiplier/Divider
30	Precision Absolute Value Circuit
31	Thermocouple Amplifier with Cold-Junction Compensation
32	Instrumentation Amp (2 Op Amp Design)
33	±200V Low Offset Operational Amplifier
34	Impedance Transforming Amplifier
35	Precision Current Sinks
36	Low Noise AGC Amplifier
37	Amplifier With Active Output Clipping
38	Low Power Amplifier With Squelch

FIGURE 1: ±200mA Servo Motor Amplifier



R_B sets the bias point for transistors Q1 and Q2. Because $V_{BE(ON)}$ varies greatly with temperature, a guardband is required to prevent Q1 and Q2 from conducting simultaneously. R_B should be selected such that the transistors do not conduct until I_M equals the op amp quiescent supply current, I_{SY} . The transistors will begin to conduct at about $V_{BE(ON)} = 0.5V$.

In this design,

$$R_B = \frac{V_{BE(ON)}}{I_{SY} + I_M} = \frac{0.5}{0.0025 + 0.0025} = 100\Omega$$

To maximize voltage swing across the motor, V1 must be minimized. If at full load $V1 = 0.2V$ with $V+ = 15V$ and $V_{BE1} = 0.8V$, the voltage across the motor will be:

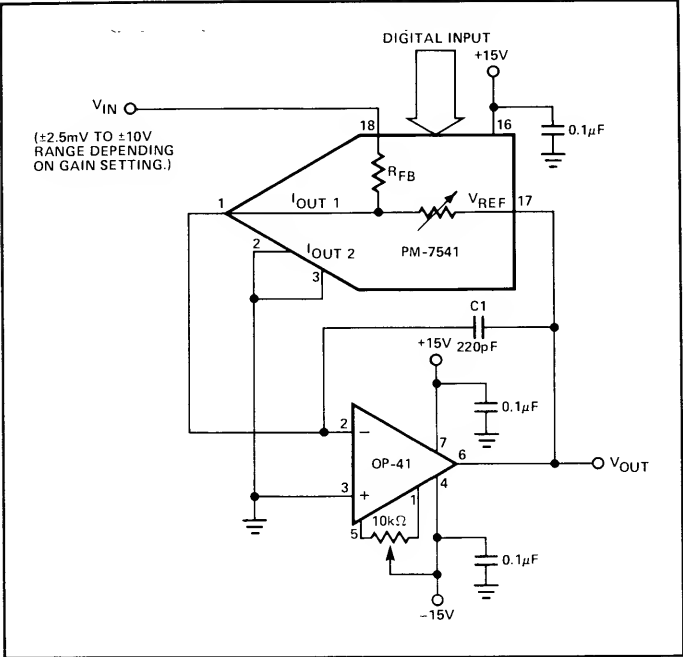
$$V_M = (V+ - 2) - V_{BE1} - V1 = (15 - 2) - 0.8 - 0.2 = 12.0V$$

V_{IN} may be scaled with a resistive divider as:

$$\frac{V_{IN}}{V1} = \frac{R1 + R2}{R2}$$

With $R1 = 240k\Omega$ and $R2 = 10k\Omega$, $V_{IN} = 5V$ will produce $I_M = 200mA$.

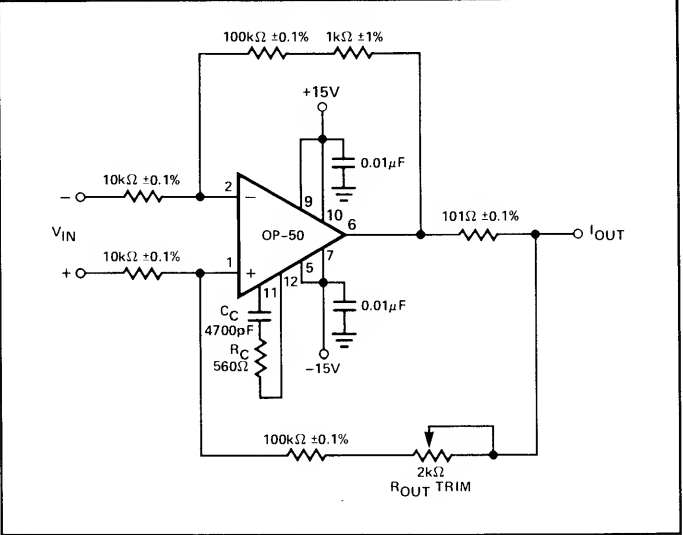
FIGURE 2: Precision Programmable Gain Amplifier



The digitally programmable gain has 12-bit accuracy over the range of -1 to -1024 and 10-bit accuracy to -4096. The low bias current of the OP-41's JFET input maintains this accuracy, while C1 limits the noise voltage bandwidth allowing accurate measurement down to microvolt levels.

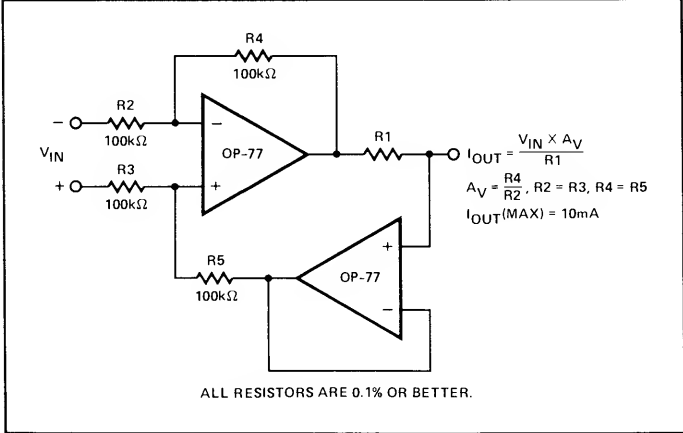
DIGITAL IN	GAIN (A_V)
4095	-1.00024
2048	-2
1024	-4
512	-8
256	-16
128	-32
64	-64
32	-128
16	-256
8	-512
4	-1024
2	-2048
1	-4096
0	OPEN LOOP

FIGURE 3: Bilateral Current Source



Compliance is better than $\pm 11V$ at an output current of 20mA, and the trimmed output resistance is typically 2M Ω with $R_L \leq 500\Omega$. For the resistor values shown, the maximum V_{IN} is 200mV.

FIGURE 4: Precision Current Pump



Accuracy of I_{OUT} is improved by using a noninverting voltage-follower in the feedback loop. To maximize voltage compliance of I_{OUT} , R1 should be minimized.

The diagram shows an OP-50 op-amp configured as a voltage follower. The non-inverting input (pin 1) is connected to the output (pin 6). The inverting input (pin 2) is connected to the output through a 1.5kΩ resistor. The op-amp is powered by +5V and -5V rails. A 0.01μF capacitor is connected from the +5V rail to ground. A 10nF ceramic capacitor is connected from the output (pin 6) to ground. The output stage consists of a MAT-02 MOSFET. The gate of the MOSFET is connected to the op-amp output (pin 6) through a 1.5kΩ resistor. The drain of the MOSFET is connected to the +5V rail through a 2.2kΩ resistor. The source of the MOSFET is connected to ground through an 820Ω resistor. The output of the MOSFET is labeled 'TTL COMPATIBLE OUTPUT'. A 1N6263 diode is connected from the output to ground. A 10nF capacitor is connected from the output to ground. A 1N6263 diode is connected from the output to the +5V rail. A 10nF capacitor is connected from the output to ground.

It is common practice with voltage comparators to ground one input terminal and to use a single-ended input. The historic reason is poor common-mode rejection on the input stage. In

The comparator is not fast, but it is very sensitive and can detect signal differences as low as $0.3\mu\text{V}$. With large input overdrives, the circuit responds in approximately $3\mu\text{s}$. If sharp transitions are needed, the use of a TTL Schmitt-trigger input is recommended. A table of Response Time vs. Input Overdrive is shown below.

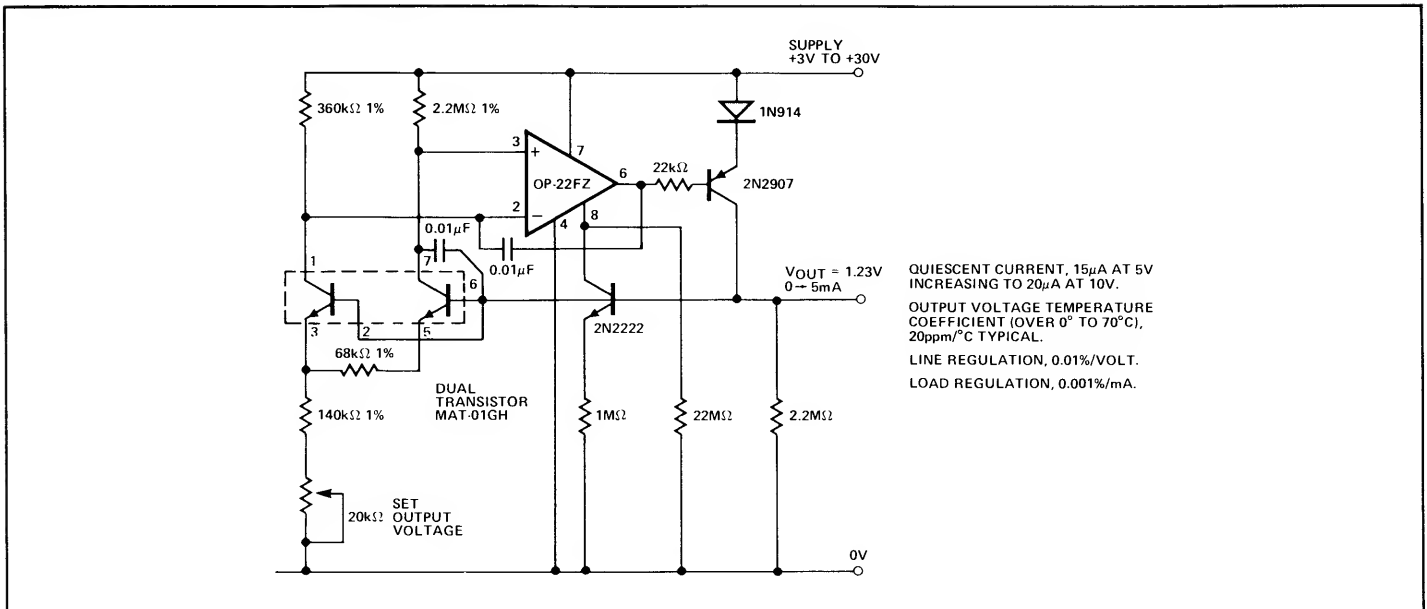
INPUT OVERDRIVE	100mV	10mV	1mV	100μV	10μV
Positive Output Delay	3.2μs	5μs	40μs	340μs	2.4ms
Negative Output Delay	1.8μs	5μs	50μs	380μs	4.5ms

The circuit diagram shows a precision current source. It features two OP-22 op-amps, A1 and A2. The input stage uses a 301kΩ 1% resistor and a 100kΩ 1% resistor to set the input voltage. A 11kΩ 1% resistor is connected to the non-inverting input of A1. The output of A1 is connected to the non-inverting input of A2. A 1MΩ resistor and a 301kΩ 1% resistor are connected to the inverting input of A2. A 91kΩ 1% resistor and a 20kΩ resistor (labeled SET OUTPUT) are connected to the inverting input of A1. The output of A2 is connected to the base of a 2N2222 transistor (O1). The emitter of O1 is connected to ground, and the collector is connected to the output terminal. A 4.7MΩ resistor and a 0.1μF capacitor are connected to the output terminal. The circuit is powered by a +6.5V ≤ VIN ≤ +30V supply and a 0V ground. A MAT-01 LED is shown in a dashed box, connected to the output terminal.

OUISCENT CURRENT $\approx 50\mu\text{A}$ AT 9V
 LOAD REGULATION, 0.001% / mA
 LINE REGULATION, 0.01% / VOLT
 TEMPERATURE COEFFICIENT, 40ppm / °C (−25°C TO +85°C)

10mA as shown, and can be increased by changing Q1 to a power transistor and proportionately increasing the set current of A2.

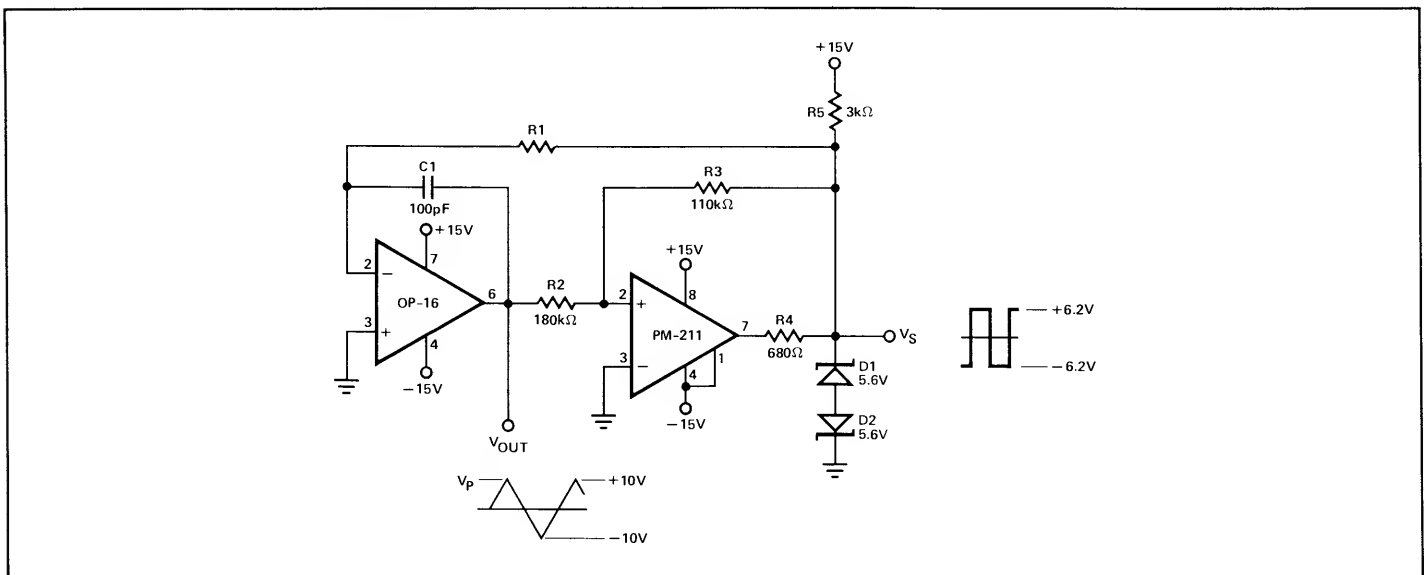
FIGURE 7: Micropower 1.23V Bandgap Reference



A micropower bandgap voltage reference operating at a quiescent current of 15μA may be constructed using an OP-22 and a MAT-01 dual transistor. The circuit provides a 1.23V

reference with better performance than micropower IC shunt regulators and has the advantages of being a series regulator.

FIGURE 8: Versatile Triangular Wave Generator



Triangular waveshapes of ±10V from 100Hz to 500kHz are obtained with values of R1 from 15MΩ to 3kΩ as given by:

$$R1 = \frac{V_s}{4V_p \cdot f_o \cdot C1}, V_s = 6.2V, V_p = 10V$$

The amplitude of the triangle wave may be adjusted via R2 as:

$$R2 = \frac{V_p \cdot 110k\Omega}{6.2V}$$

The circuit diagram shows a precision current source with a range switch. The input signal is applied to the inverting input of an OP-41EJ operational amplifier through a 4.7kΩ resistor (R1). The non-inverting input is grounded. The feedback path from the output to the inverting input consists of a 100pF capacitor (C1) in parallel with a 2.4MΩ resistor (R2). The output of the op-amp is connected to the emitter of a 1/2 MAT-02EH PNP transistor (Q1A) through a 3kΩ resistor (R3). The collector of Q1A is connected to a 15V supply through a 4kΩ resistor (R12). The base of Q1A is connected to the base of another 1/2 MAT-02EH PNP transistor (Q1B) and to the emitter of a 2N2222 NPN transistor (Q3). The collector of Q3 is connected to the 15V supply. The emitter of Q1B is connected to ground through a 1N914 diode (D1). A range switch (S1) selects between different current values: 100pA, 1nA, 10nA, 100nA, 1μA, 10μA, and 100μA. These values are achieved by switching between different resistors (R4, R5, R6, R7, R8, R9, R10, R11) in the feedback path of the op-amp. A 100μA meter is connected in series with the output of the op-amp. A 511Ω resistor (R12) is connected between the 15V supply and the output of the op-amp.

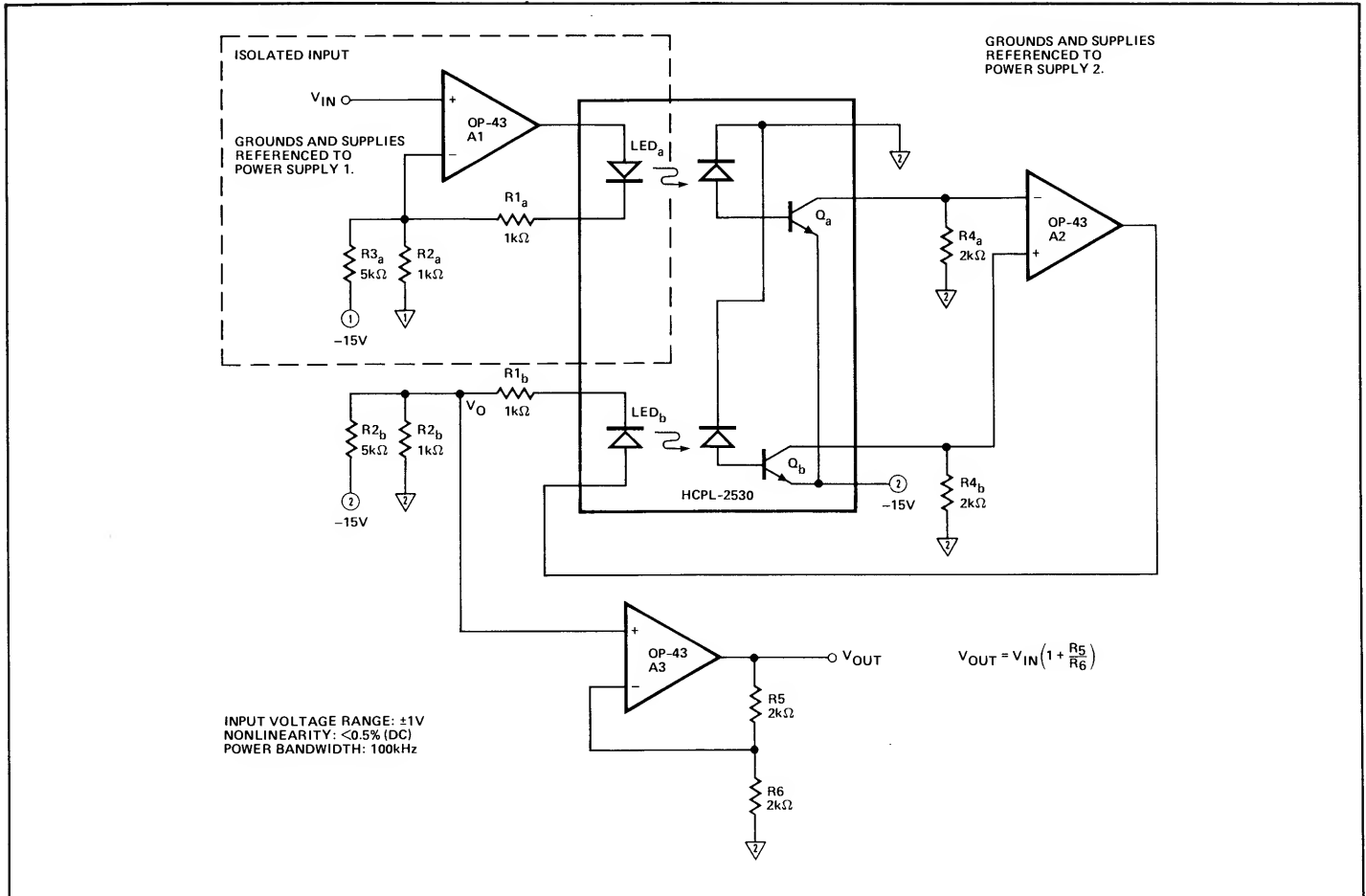
The low V_{OS} and exceptionally good log conformance of the MAT-02 assure high accuracy over the full 6 decade operating range.

C_C is selected to smooth the loop response.

The diagram shows a photodiode amplifier circuit. A photodiode, labeled HP5082-4203, is connected in reverse bias. Its cathode is connected to the inverting input of an OP-41 operational amplifier and to a positive supply rail. The anode is connected to ground. The non-inverting input of the OP-41 is connected to ground. The feedback network consists of a 4pF capacitor connected between the output and the inverting input. Additionally, there is a voltage divider consisting of two $1\text{M}\Omega$ resistors in series, with a $1\text{k}\Omega$ resistor connected to ground from the midpoint. The output voltage is labeled $V_{\text{OUT}} = 0.5\text{V/nW}$.

This circuit produces an output voltage proportional to light input over a 60dB range. The 5pA input bias current of the OP-41 assures a low output voltage offset.

FIGURE 12: Isolation Amplifier



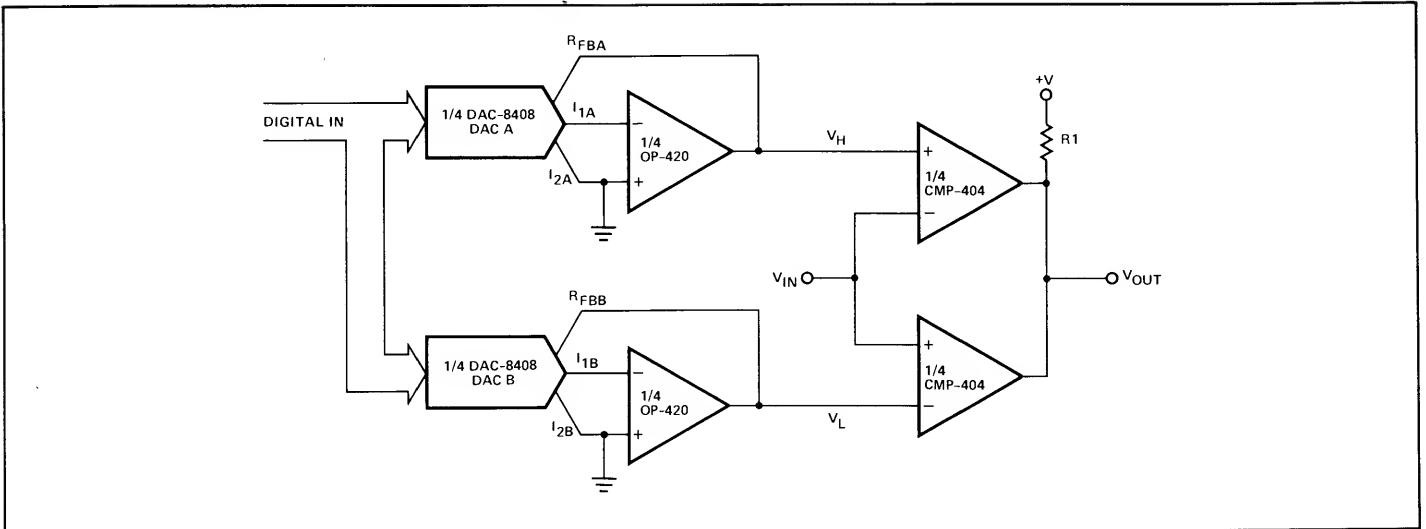
In conjunction with two optocouplers, or a dual optocoupler such as the Hewlett-Packard HCPL-2530, three OP-43's can be combined to create an isolation amplifier. In this sort of amplifier, the input and the output operate on separate power supplies, allowing extremely high common-mode voltages to be dealt with. In industrial applications, an isolation amplifier protects instrumentation from high voltages at the sensing site. When interfacing with a computing system, an isolation amplifier will protect the rest of the system from a sensor which accidentally becomes shorted to a high voltage.

The isolation amplifier operates on the principle that the nonlinearities of one optocoupler will be tracked by the nonlinearities of another, if they are well matched. By using an optocoupler in the feedback loop of A2, nonlinearities of the isolating optocoupler will be cancelled. V_O will equal V_{IN} plus an offset created by imperfect matching between a and b side resistors and optocouplers.

A3 is an output buffer for the isolation amplifier. The low bias current ensures that it does not affect the voltage it is amplifying. Gain is realized in this stage, and any offsets induced in the previous stages may be corrected by offsetting this op amp. Although shown in the circuit as a simple gain stage, this output amplifier may take any form desired. It may be configured as a filter or other waveshaping circuit as needed. The only requirement is that the buffer not disturb the currents in the optocoupler feedback circuit, thus noninverting amplifier configurations are preferred. For highest linearity, the currents in the two LEDs should track as closely as possible.

With stable supplies, the circuit has excellent response and displays less than 0.5% DC nonlinearity with a $2V_{p-p}$ signal. The high speed of the OP-43 gives the circuit a power bandwidth of 100kHz, while the majority of the power budget is consumed in biasing the LEDs. The dual optocoupler provides isolation against 600VDC common-mode voltages. Higher isolations may be achieved using two separate optocouplers, such as HP's 6N136.

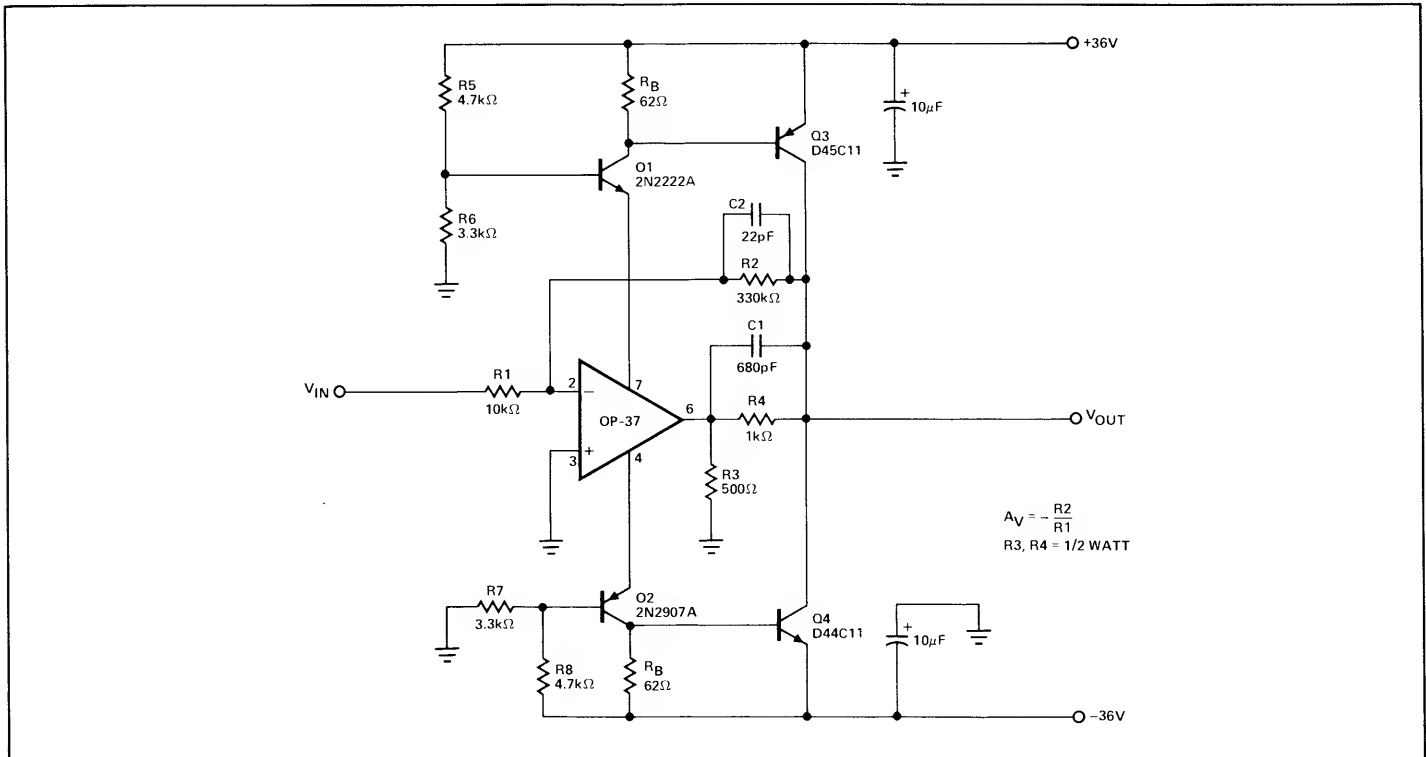
FIGURE 13: Dual Programmable Window Comparator



Only three ICs are required to fully implement two independent programmable window comparators. The quad, latched, 8-bit CMOS DAC-8408 together with the quad micropower OP-420 provide digitally-programmable HIGH and LOW thresholds to

the CMP-404, quad low-power comparator. The outputs of the threshold comparators are wire-ORed with a common pull-up resistor producing $V_{OUT} = +V$ only when $V_L < V_{IN} < V_H$. Total supply current for the full circuit is less than 2mA.

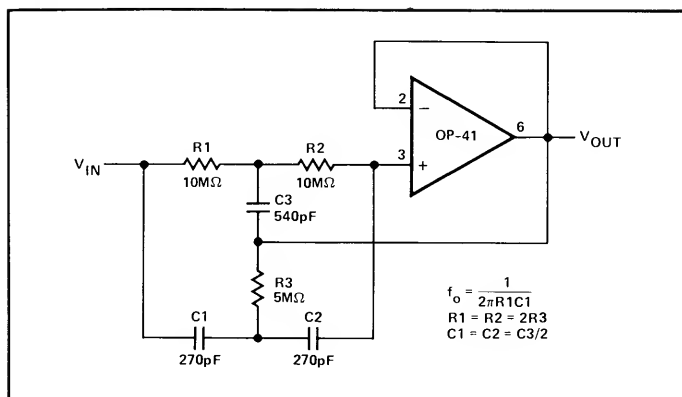
FIGURE 14: $\pm 36V$ Low Noise Operational Amplifier



An OP-37 provides a low-noise front end for this amplifier which is capable of delivering over $\pm 200\text{mA}$ to a load with a 70V peak-to-peak output swing. Transistors Q1 and Q2 are series regulators stepping down the supply voltage for the OP-37 to

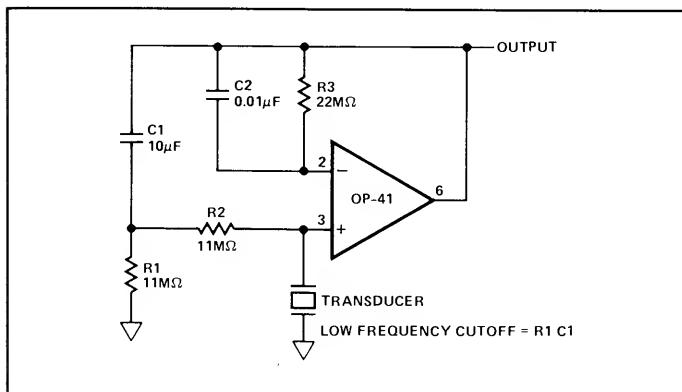
$\pm 15V$, while transistors Q3 and Q4 provide the high current output drive. R3 and R4 form an output voltage gain stage whose gain, $A_V = 3$, is reduced to unity at high frequencies by C1 to maintain stability.

FIGURE 15: High Q Notch Filter



The low bias current and high input impedance of the OP-41 enable small value capacitors and large resistors to be used in this 60Hz notch filter. The 5pA bias current only develops 100 μ V across R1 and R2.

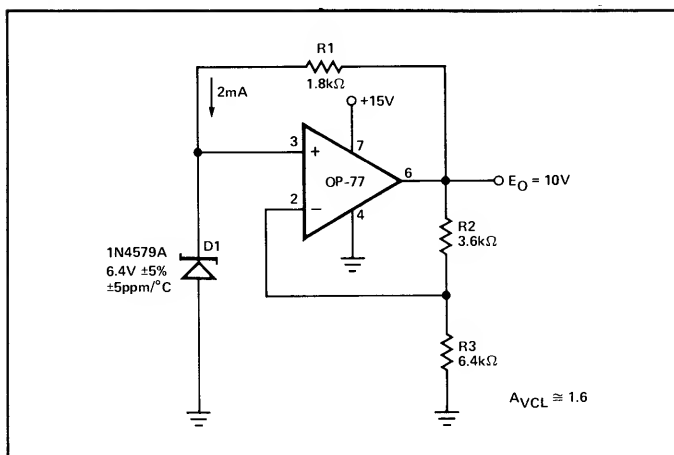
FIGURE 16: Piezoelectric Transducer Amplifier



Piezoelectric transducers often require a high-input-resistance amplifier. The OP-41 can provide input resistance in the range of $10^{12}\Omega$, however, a DC return for bias current is needed. To maintain a high R_{IN} , large value resistors above $22M\Omega$ are often required. These may not be practicable.

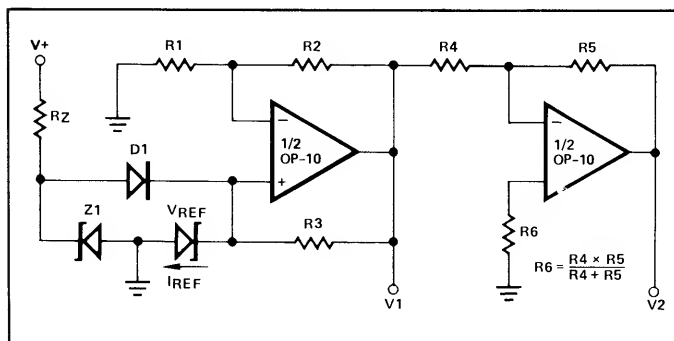
Using this circuit, input resistances that are orders of magnitude greater than the values of the DC return resistors can be obtained. This is accomplished by bootstrapping the resistors to the output. With this arrangement, the lower cutoff frequency is determined more by the RC product of R1 and C1 than it is by resistor values and the equivalent capacitance of the transducer.

FIGURE 17: High Stability Voltage Reference



The simple bootstrapped voltage reference provides a precise 10V virtually independent of changes in power supply voltage, ambient temperature, and output loading. Correct zener operating current of exactly 2mA is maintained by R1, a selected 5ppm/°C resistor, connected to the regulated output. Accuracy is primarily determined by three factors: the 5ppm/°C temperature coefficient of D1, 1ppm/°C ratio tracking of R2 and R3, and operational amplifier V_{OS} errors. The OP-77, with TCV_{OS} of $0.3\mu V/^{\circ}C$, contributes only 0.05ppm/°C of output error, thus effectively eliminating TCV_{OS} as an error consideration.

FIGURE 18. Precision Dual Tracking Voltage References



Precision dual tracking voltage references using a single reference source are easily constructed using OP-10. These references exhibit excellent stability vs. temperature/time, low noise, and excellent power supply rejection.

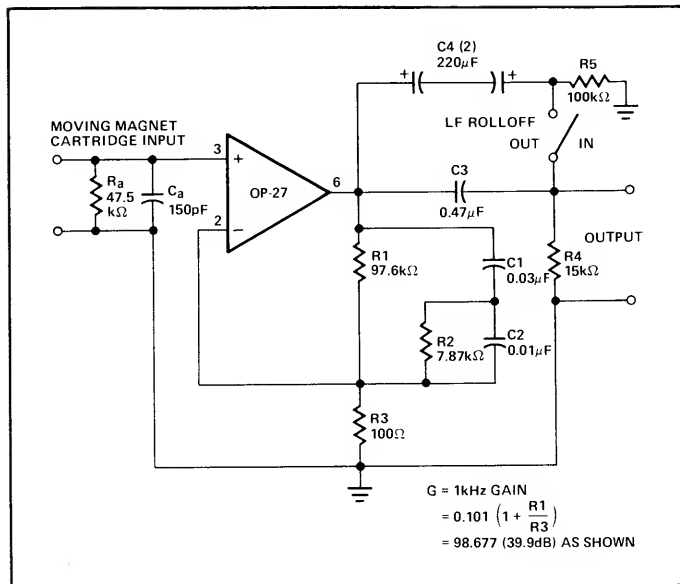
In the circuit shown, R3 should be adjusted to set I_{REF} to operate V_{REF} at its minimum temperature coefficient current. Proper circuit start-up is assured by R7, Z1, and D1.

$$V_{Z1} \leq V_{REF} \qquad V1 = V_{REF} \left(1 + \frac{R2}{R1} \right)$$

$$R3 = \frac{(V1 - V_{REF})}{I_{REF}} \quad V2 = V1 \left(\frac{-R5}{R4} \right)$$

Output Impedance (ΔI_L : 1.0mA—5.0mA) $0.25 \times 10^{-3} \Omega$

FIGURE 19: RIAA Phone Pre-Amplifier



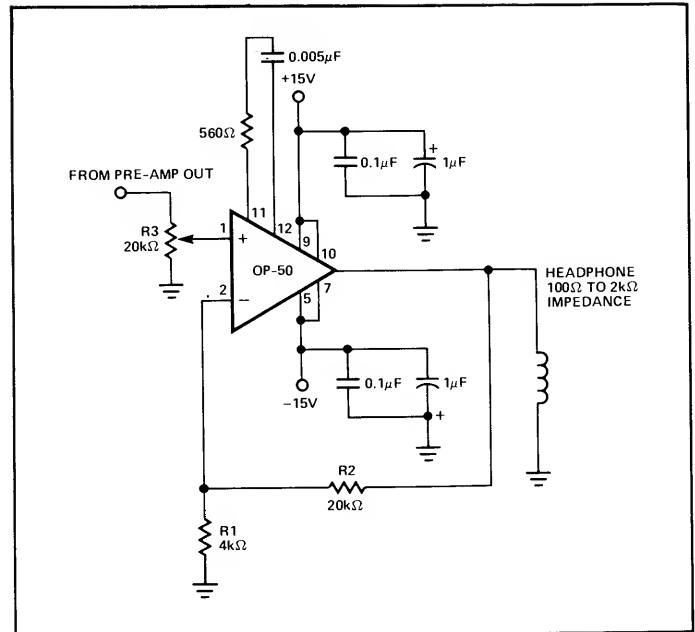
The OP-27 is used in this phono pre-amplifier circuit because of its low noise characteristics. It contributes only $3.2\text{nV}/\sqrt{\text{Hz}}$ voltage noise and $0.45\text{pA}/\sqrt{\text{Hz}}$ current noise to the circuit. To minimize noise from other sources, R3 is set to 100Ω . This generates additional voltage noise of only $1.3\text{nV}/\sqrt{\text{Hz}}$. With a $1\text{k}\Omega$ source, the circuit noise measures 63dB below a 1mV reference level, unweighted, in a 20kHz bandwidth.

R1, R2, C1, and C2 form a very accurate RIAA network with standard component values providing the necessary time constants of 3180, 318, and $75\mu\text{sec}$. For initial equalization accuracy and stability, precision metal-film resistors and film capacitors of polystyrene or polypropylene are recommended since they have low voltage coefficients, dissipation factors, and dielectric absorption. (High-K ceramic capacitors should be avoided here, though low-K ceramics—such as NPO types, which have excellent dissipation factors, and somewhat lower dielectric absorption—can be considered for small values.)

Capacitor C3 and resistor R4 form a simple -6dB-per-octave rumble filter, with a corner at 22Hz. As an option, the switch-selected shunt capacitor C4, a nonpolarized electrolytic, bypasses the low-frequency rolloff. Placing the rumble filter's high-pass action after the pre-amp has the desirable result of discriminating against the RIAA-amplified low-frequency noise components and pickup-produced low-frequency disturbances.

This circuit is capable of very low distortion over its entire range, generally below 0.01% at levels up to $7V_{\text{rms}}$. At 3V output levels, it will produce less than 0.03% total harmonic distortion at frequencies up to 20kHz.

FIGURE 20: Headphone Amplifier



For low level Pre-Amp Out signals, the amplifier gain may be increased by reducing R1 according to:

$$R1 = \frac{20\text{k}\Omega}{A_v - 1}$$

Note that two amplifiers are required for stereo applications.

Performance: ($V_{\text{OUT}} = 6V_{\text{RMS}}$, $R1 = 4\text{k}\Omega$)

T.H.D @ 100Hz = 0.0025%

@ 1kHz = 0.003%

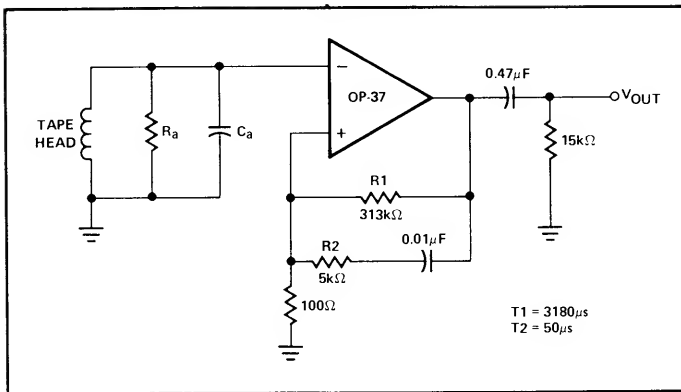
@ 10kHz = 0.011%

Signal-to-Noise Ratio $\geq 80\text{dB}$

Response Flatness = $\pm 0.4\text{dB}$ from 10Hz to 20kHz

Bandwidth = -3dB @ 56kHz

FIGURE 21: NAB Tape Head Pre-Amplifier



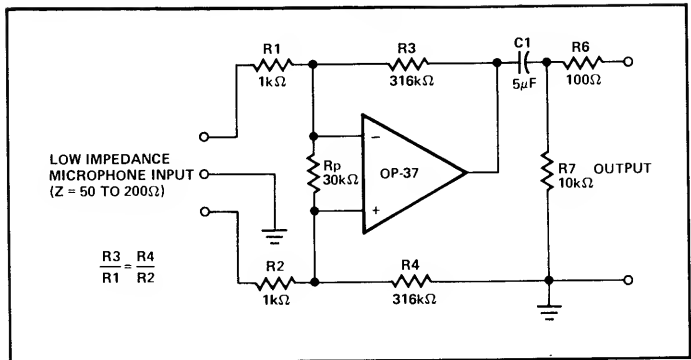
A pre-amplifier for NAB tape playback is similar to an RIAA phono pre-amp, though more gain is typically demanded, along with equalization requiring a heavy low-frequency boost.

The network values of this configuration yield a 50dB gain at 1kHz, and a DC gain greater than 70dB. Thus, the worst-case output offset is just over 500mV. The DC resistance of the tape head will add to this a bias-current-induced offset voltage. To minimize this contribution, the head's DC resistance should be low, preferably below 1kΩ. A single 0.47μF output capacitor can block the final output offset without affecting the dynamic range.

The tape head can be coupled directly to the amplifier input, since the worst-case bias current of 80nA with a 400mH, 100μin. head (such as the PRB2H7K) will not be troublesome.

One potential tape head problem is presented by amplifier bias current transients at power-up or power-down which can magnetize a head. Although the OP-37 is free of these bias current transients, it is always good design practice to control the speed of power supply rise and fall to eliminate transients.

FIGURE 22: Microphone Pre-Amplifier

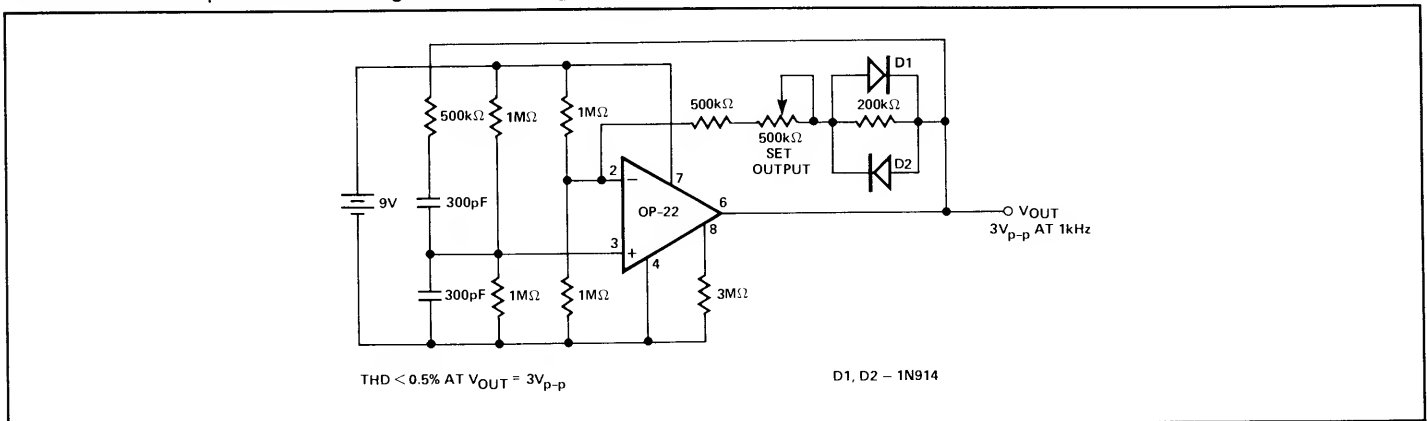


This simple, but effective, fixed-gain transformerless microphone pre-amp amplifies differential signals from low-impedance microphones by 50dB, and has an input impedance of 2kΩ. Because of the high working gain of the circuit, an OP-37 helps to preserve bandwidth, which will be 110kHz. As the OP-37 is a decompensated device (minimum stable gain of 5), a dummy resistor, R_p , may be necessary, if the microphone is to be unplugged. Otherwise the 100% feedback from the open input may cause the amplifier to oscillate.

Common-mode input-noise rejection will depend upon the match of the bridge-resistor ratios. Either close-tolerance (0.1%) types should be used, or R4 should be trimmed for best CMRR. All resistors should be metal-film types for best stability and low noise.

Noise performance of this circuit is limited more by the input resistors R1 and R2 than by the op amp, as R1 and R2 each generate a $4\text{nV}/\sqrt{\text{Hz}}$ noise, while the op amp generates a $3.2\text{nV}/\sqrt{\text{Hz}}$ noise. The rms sum of these predominant noise sources will be about $6\text{nV}/\sqrt{\text{Hz}}$, equivalent to 0.9μV in a 20kHz noise bandwidth, or nearly 61dB below a 1mV input signal. Measurements confirm this predicted performance.

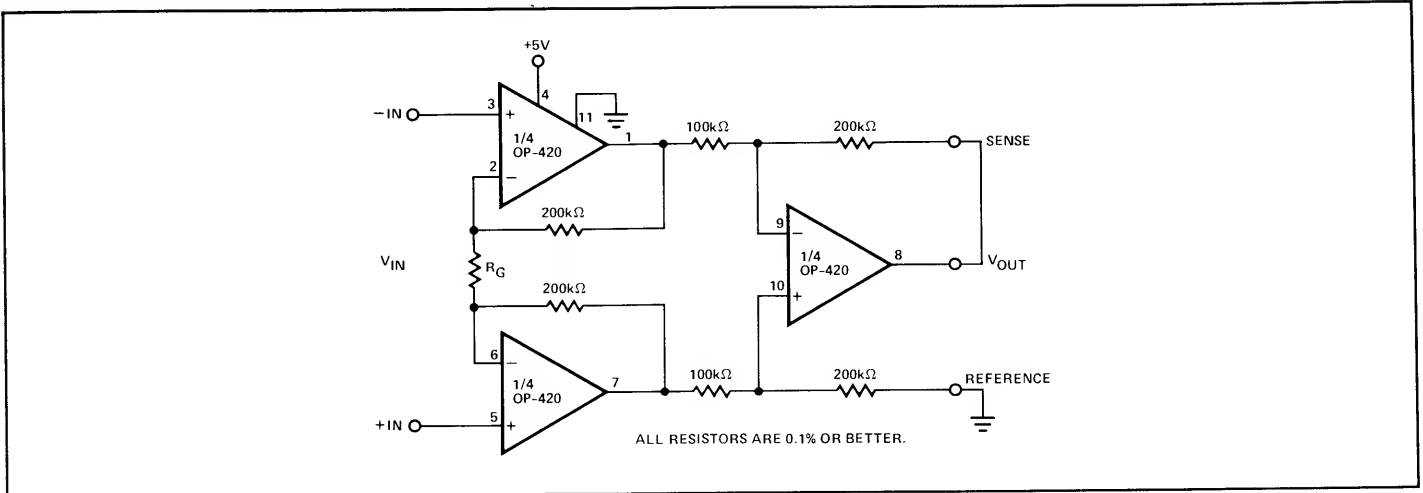
FIGURE 23: Micropower Wien-Bridge Oscillator ($P_d < 500\mu\text{W}$)



Requiring less than 60μA of supply current, this micropower Wien-bridge oscillator is ideal for battery-powered instrumentation. Output level is controlled by nonlinear elements D1 and

D2. When adjusted for 3V_{p-p} output, the distortion level is below 0.5% at 1kHz.

FIGURE 24: Micropower Instrumentation Amplifier

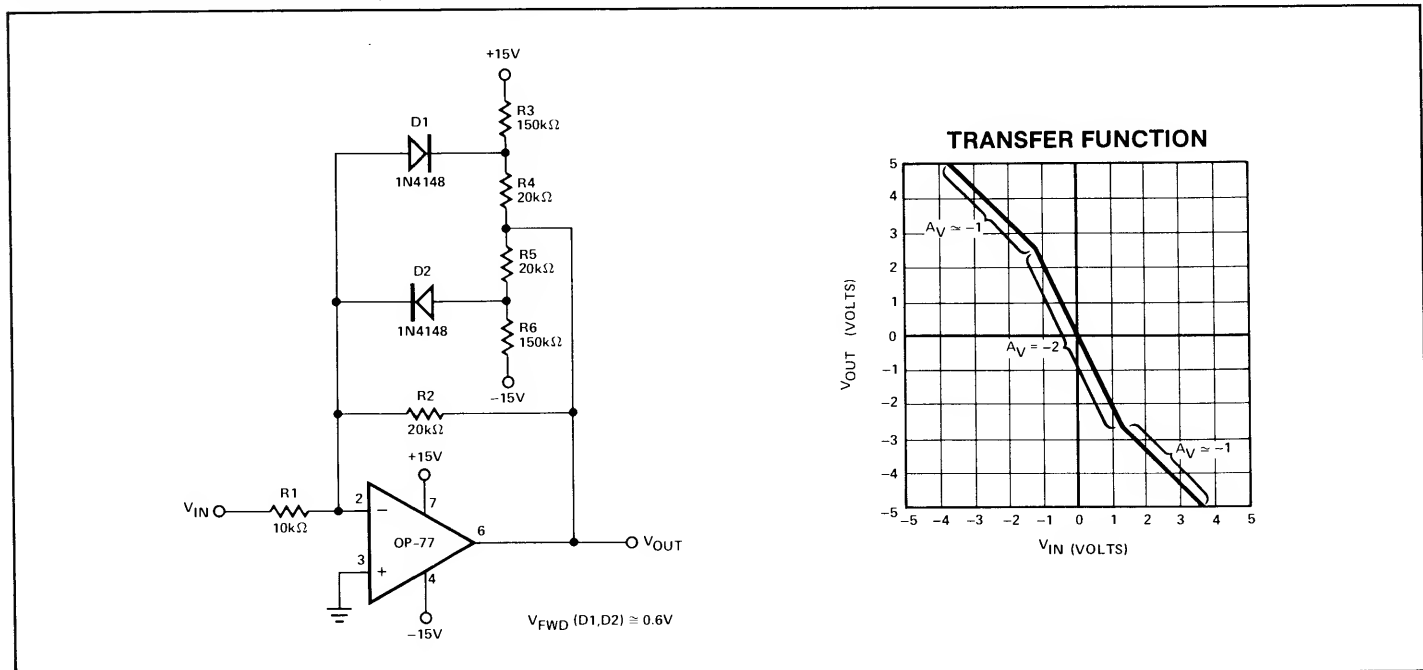


This instrumentation amplifier requires only $200\mu\text{A}$ total quiescent current ($V_{\text{CM}} = 0\text{V}$) and operates on single voltage supplies from $+1.6\text{V}$ to $+36\text{V}$. Input and output voltage range is

0V to $(V^+ - 1.5)$ volts with CMRR above 100dB . Differential gain, A_V , is adjusted with a single resistor, R_G , as given by:

$$R_G = \frac{800\text{k}\Omega}{A_V - 2}$$

FIGURE 25: Piecewise-Linear Amplifier (Decreasing Gain)



This circuit is useful in linearizing a nonlinear input signal or creating a nonlinear output function from a linear input. At $V_{\text{OUT}} = 0\text{V}$, both D1 and D2 are reverse biased, and $V_{\text{OUT}}/V_{\text{IN}} = -R_2/R_1$. As V_{IN} goes positive, V_{OUT} becomes negative according to that gain until a threshold is reached, $-(V_{\text{OUT}} + V_{\text{FWD}})/R_4 = 15\text{V}/R_3$, where D1 becomes forward biased. For more positive values of V_{IN} , the gain is:

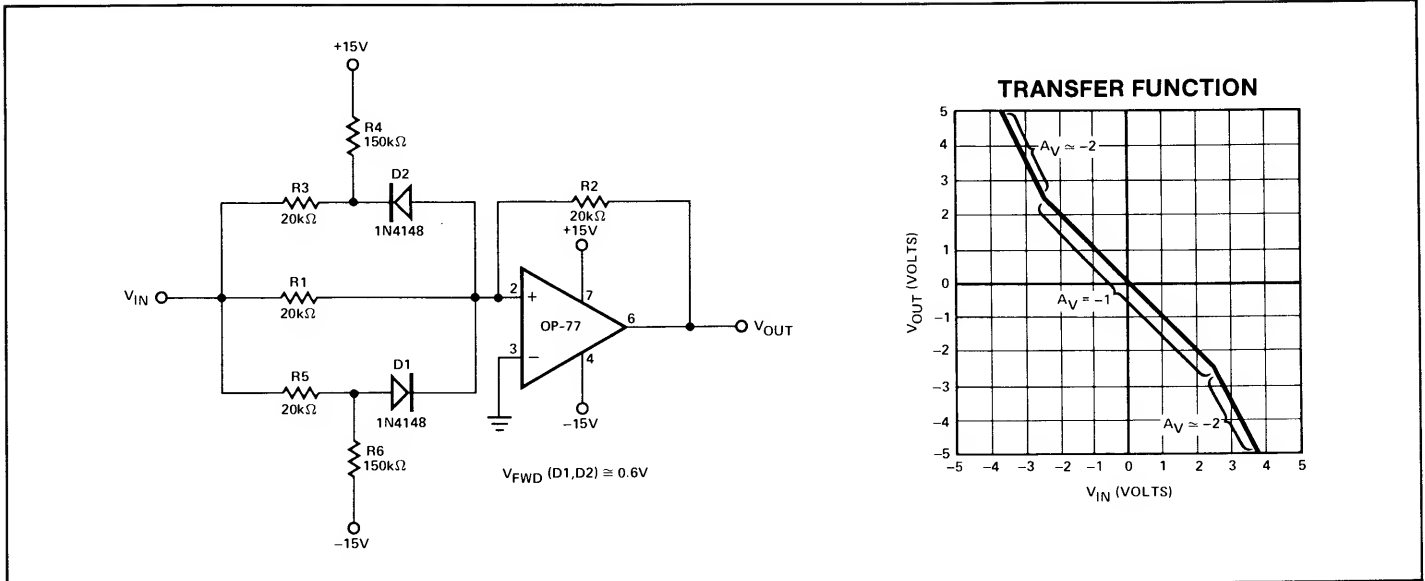
$$\frac{V_{\text{OUT}}}{V_{\text{IN}}} = -\frac{(R_2 \cdot R_4)}{(R_2 + R_4)R_1} - \frac{R_2 \cdot V_{\text{FWD}}}{(R_2 + R_5)V_{\text{IN}}}$$

A similar action occurs as V_{IN} goes negative. Beyond the point where D2 becomes forward biased, $(V_{\text{OUT}} - V_{\text{FWD}})/R_5 = 15\text{V}/R_6$, the gain is:

$$\frac{V_{\text{OUT}}}{V_{\text{IN}}} = -\frac{(R_2 \cdot R_5)}{(R_2 + R_5)R_1} - \frac{R_2 \cdot V_{\text{FWD}}}{(R_2 + R_5)V_{\text{IN}}}$$

Additional diode/resistor combinations can be added to further contour the gain.

FIGURE 26: Piecewise-Linear Amplifier (Increasing Gain)



This circuit performs the linear-to-nonlinear or nonlinear-to-linear transformation by increasing gain beyond fixed thresholds. At $V_{IN} = 0V$, both $D1$ and $D2$ are reverse biased, and $V_{OUT}/V_{IN} = -R2/R1$. As V_{IN} goes positive beyond the threshold, $(V_{IN} - V_{FWD})/R5 = 15V/R6$, $D1$ conducts, and the gain becomes:

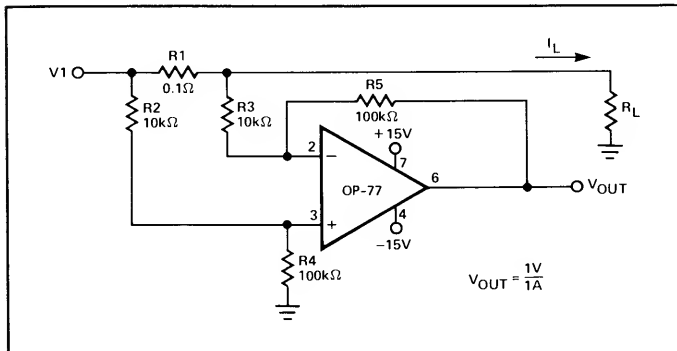
$$\frac{V_{OUT}}{V_{IN}} = -\frac{R2(R1 + R5)}{(R1 \cdot R5)} + \frac{V_{FWD} \cdot R2}{V_{IN} \cdot R5}$$

As V_{IN} goes negative beyond the threshold, $-(V_{IN} + V_{FWD})/R3 = 15V/R4$, $D2$ conducts, and the gain becomes:

$$\frac{V_{OUT}}{V_{IN}} = -\frac{R2(R1 + R3)}{(R1 \cdot R3)} + \frac{V_{FWD} \cdot R2}{V_{IN} \cdot R3}$$

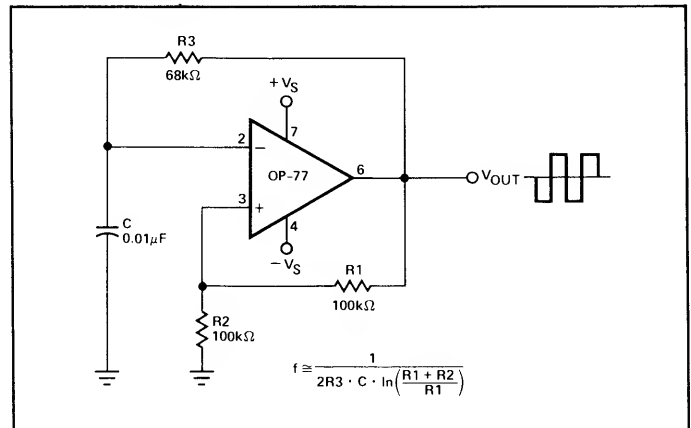
Additional diode/resistor combinations can be added to further contour the gain.

FIGURE 27: Current Monitor Circuit



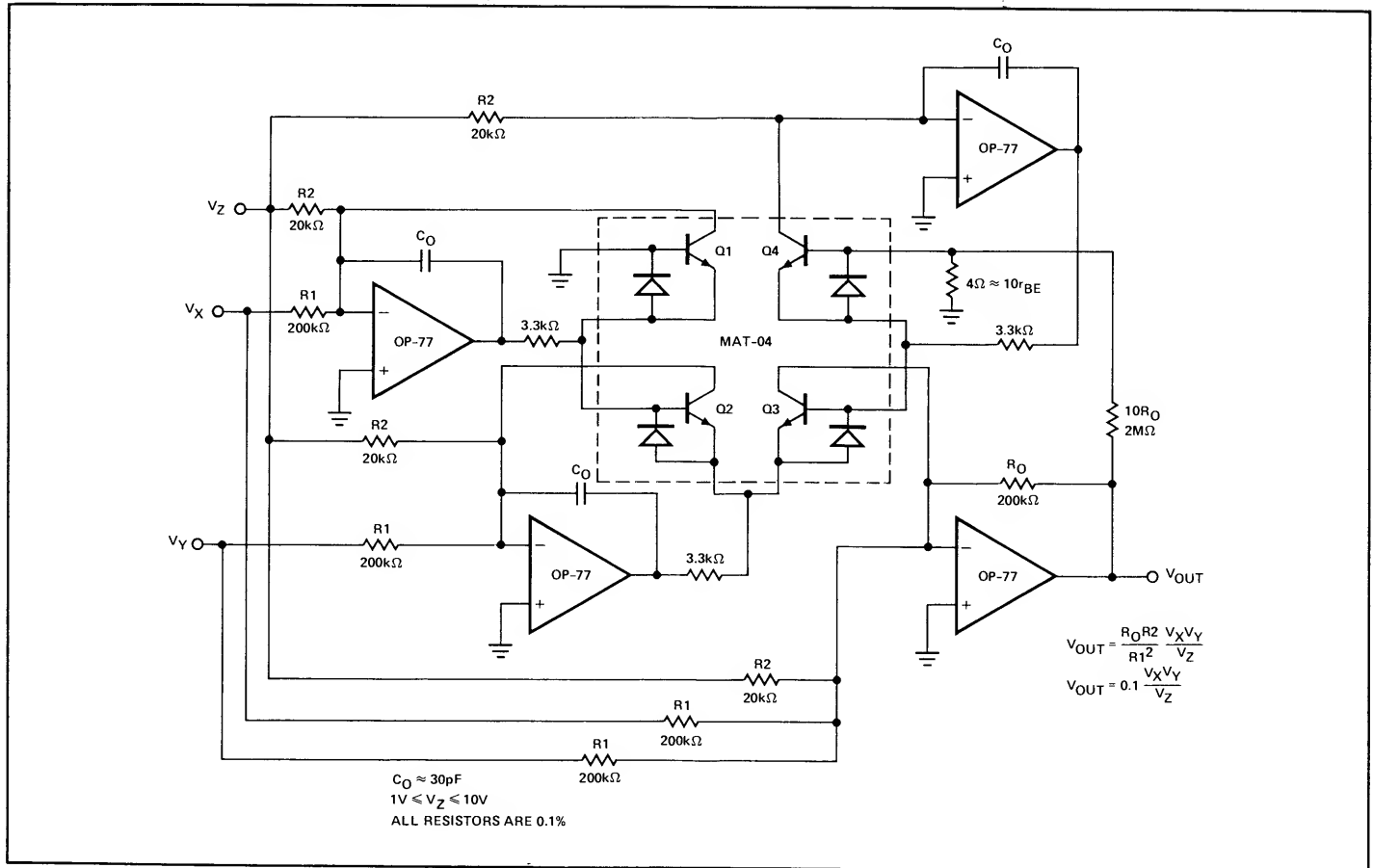
This versatile monitor circuit can typically sense current at any point between the $\pm 15V$ supplies ($|V1| < 14.3V$ guaranteed). This makes it ideal for sensing current in applications such as full bridge drivers where bi-directional current is associated with large common-mode voltage changes. The 120db CMRR of the OP-77 makes the amplifier's contribution to common-mode error negligible, leaving only the error due to the resistor ratio inequality. Ideally, $R2/R4 = R3/R5$. This is best trimmed via $R4$.

FIGURE 28: Free-Running Square-Wave Oscillator



This simple oscillator creates a square-wave output of $\pm(V_S - 2V)$ at 1kHz for the values shown.

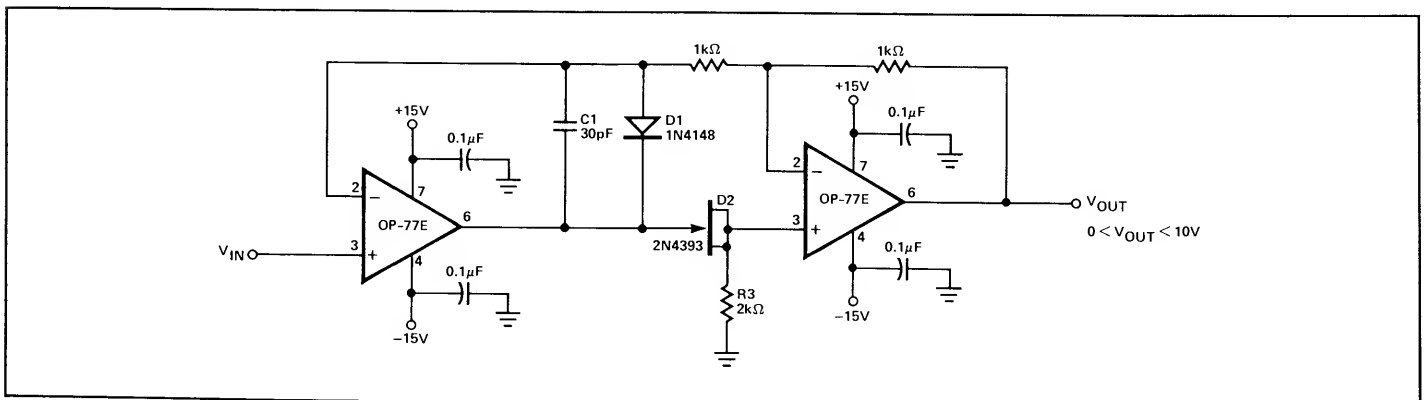
FIGURE 29: Precision Analog Multiplier/Divider



This multiplier/divider achieves its excellent performance through the low emitter resistance, r_{BE} , and superior V_{OS} matching of MAT-04 quad transistor array. In this circuit,

linearity error due the transistors is less than $\pm 0.1\%$. The OP-77 helps maintain accuracy with a V_{OS} less than $25\mu\text{V}$. For even higher accuracy the offset voltages may be nulled.

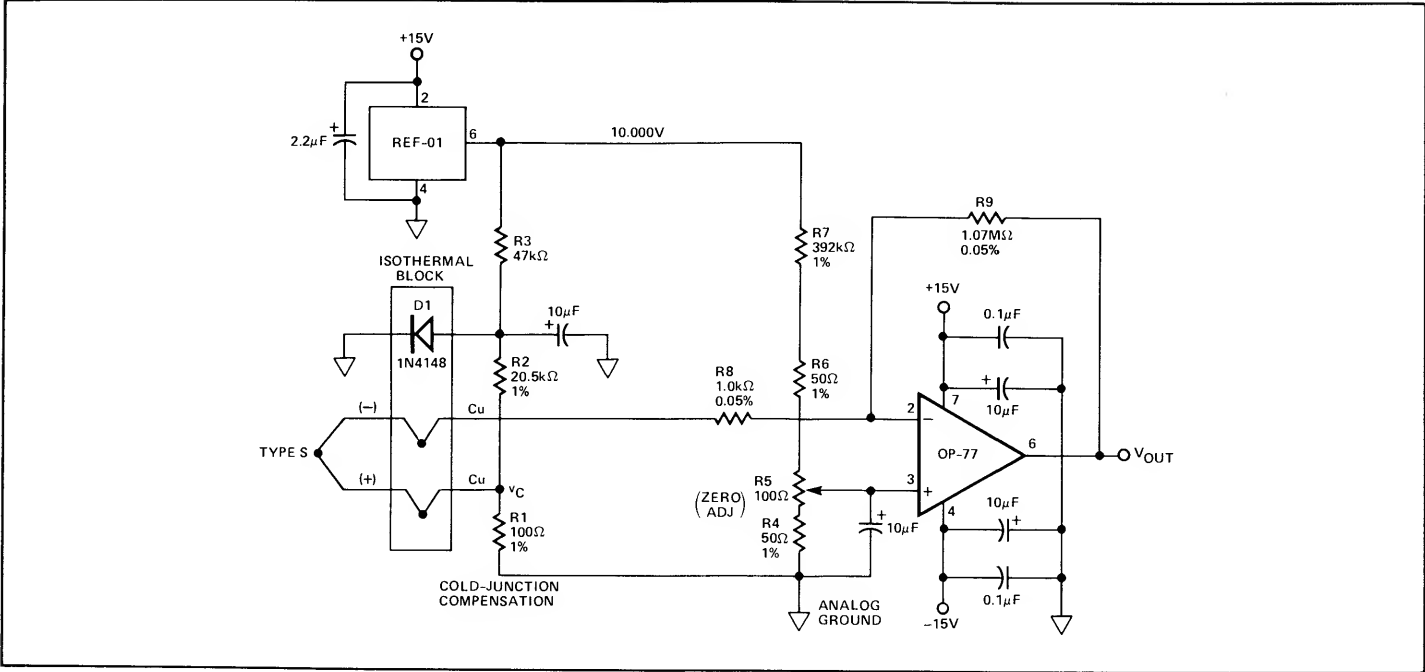
FIGURE 30: Precision Absolute Value Amplifier



The high gain and low TCV_{OS} assure accurate operation with inputs from microvolts to volts. In this circuit, the signal always

appears as a common-mode signal to the op amps. The OP-77E CMRR of $1\mu\text{V/V}$ assures errors of less than 2ppm.

FIGURE 31: Thermocouple Amplifier With Cold-Junction Compensation



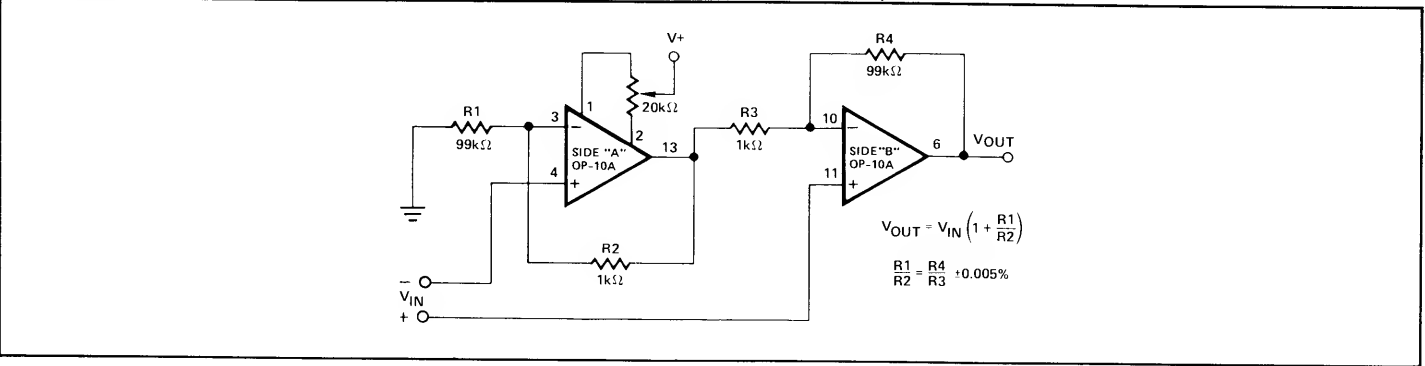
The high gain, low noise, and low offset drift of the OP-77 can be used to create a thermocouple amplifier with superb linearity. They combine to give a total accuracy typically better than $\pm 0.5^{\circ}\text{C}$.

Cold-junction compensation is performed by R1, R2, and D1 which is mounted isothermally with the thermocouple terminating junctions. Calibration is done using R5 after the circuit has stabilized for about 15 minutes. A copper wire short is applied across the terminating junctions simulating a zero $^{\circ}\text{C}$ ice point. R5 is then adjusted for 0.000V output. The short is then removed, and the amplifier is ready for use.

This amplifier can be used for type S, J, and K thermocouples with the appropriate resistor values as shown below. R9 is chosen to give a +10.000V output for a $1,000^{\circ}\text{C}$ measurement.

SEEBECK				
TYPE	COEFFICIENT, α	R1	R2	R9
K	$39.2\mu\text{V}/^{\circ}\text{C}$	110Ω	$5.76\text{k}\Omega$	$102\text{k}\Omega$
J	$50.2\mu\text{V}/^{\circ}\text{C}$	100Ω	$4.02\text{k}\Omega$	$80.6\text{k}\Omega$
S	$10.3\mu\text{V}/^{\circ}\text{C}$	100Ω	$20.5\text{k}\Omega$	$1.07\text{M}\Omega$

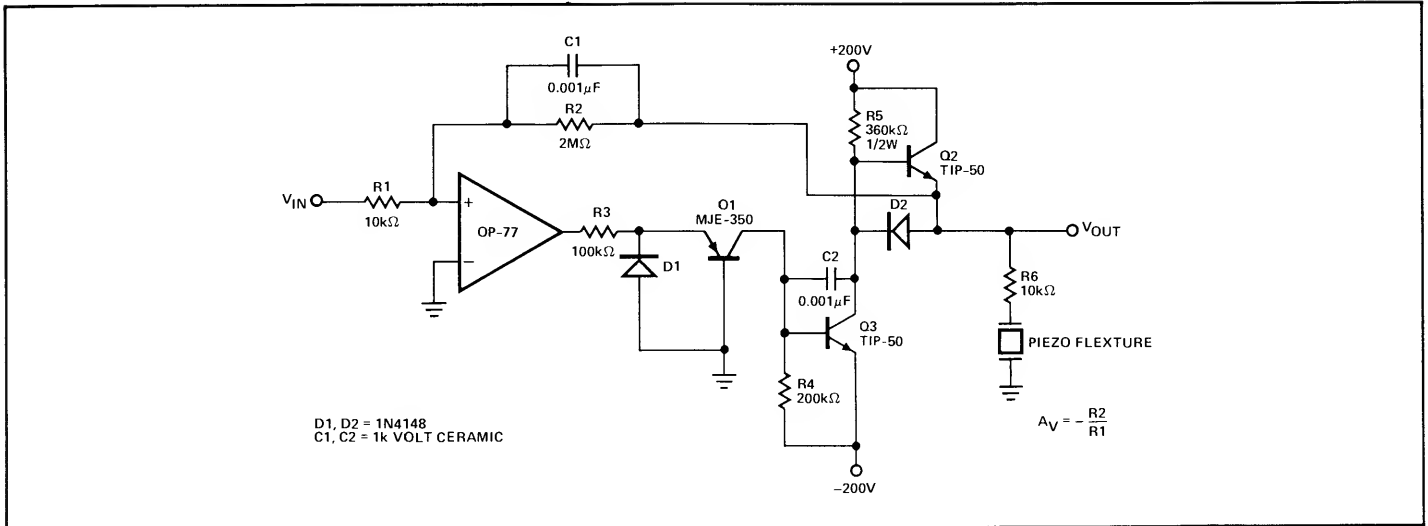
FIGURE 32: Instrumentation Amplifier (2 Op Amp Design)



This differential amplifier offers high input impedance and a power supply rejection ratio greater than 100dB. Because the high circuit gain occurs in Side "B"; Side "A" offset should be

adjusted with respect to V_{OUT} . This simultaneously corrects for Side "B" offset voltage. For the circuit values given, $A_V = 100$.

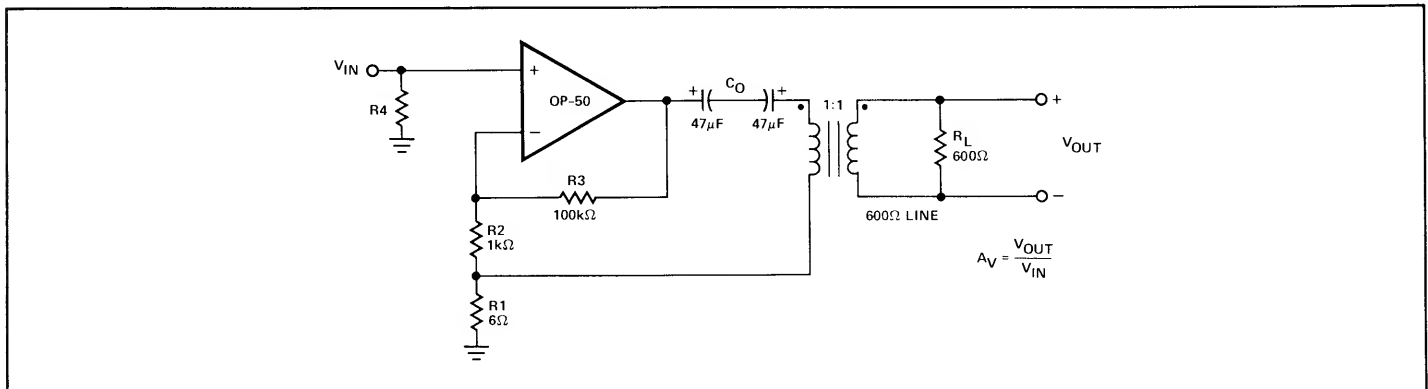
FIGURE 33: $\pm 200\text{V}$ Low Offset Operational Amplifier



The OP-77 is the heart of this high voltage amplifier designed to drive piezo flexure elements in precise positioning applications. The high gain and low offset voltage of the OP-77 produce an accurate, stable drive voltage to the piezo device allowing predictable, repeatable sub-micron movements to be easily controlled.

The output of the OP-77 creates a proportional current drive through the common-base connected Q1 to the base of Q3. Q3 forms a Class A amplifier with bias resistor R5, and transistor Q2 is simply an emitter-follower used for output current boost. R6 is necessary to prevent oscillation caused by the capacitive loading of the piezo device on the output of the amplifier.

FIGURE 34: Impedance Transforming Amplifier



This is an efficient, flexible circuit simulating a source impedance equal to the load impedance. By definition, if $R_S = R_L$, then,

$$A_V = \frac{A_{V(\text{UNLOADED})}}{2}$$

The unloaded gain is roughly R_3/R_2 . When the output is loaded, a second feedback loop is closed whose gain, $A_V \approx R_L/R_1$, combines in parallel with $A_{V(\text{UNLOADED})}$ to give:

$$A_{V(\text{LOADED})} = \frac{A_{V(\text{UNLOADED})} \cdot A_V}{A_{V(\text{UNLOADED})} + A_V}$$

$$\text{If } R_3/R_2 = R_L/R_1, \text{ then } A_{V(\text{LOADED})} = \frac{A_{V(\text{UNLOADED})}}{2}$$

These approximations assume that $R_1 \ll R_2$ and $R_2 \ll R_3$. The OP-50 requires no compensation for the circuit values shown and can easily drive the 600Ω line.

POSITIVE CURRENT SINK

$I_O = \frac{V_{IN}}{R_1}$
 $V_{IN} > 0V$
 FULL SCALE OF 1V,
 $I_O = 1A/V$

POSITIVE CURRENT SOURCE

$I_O = \frac{V_{IN}}{R_1}$
 $V_{IN} \leq 0V$

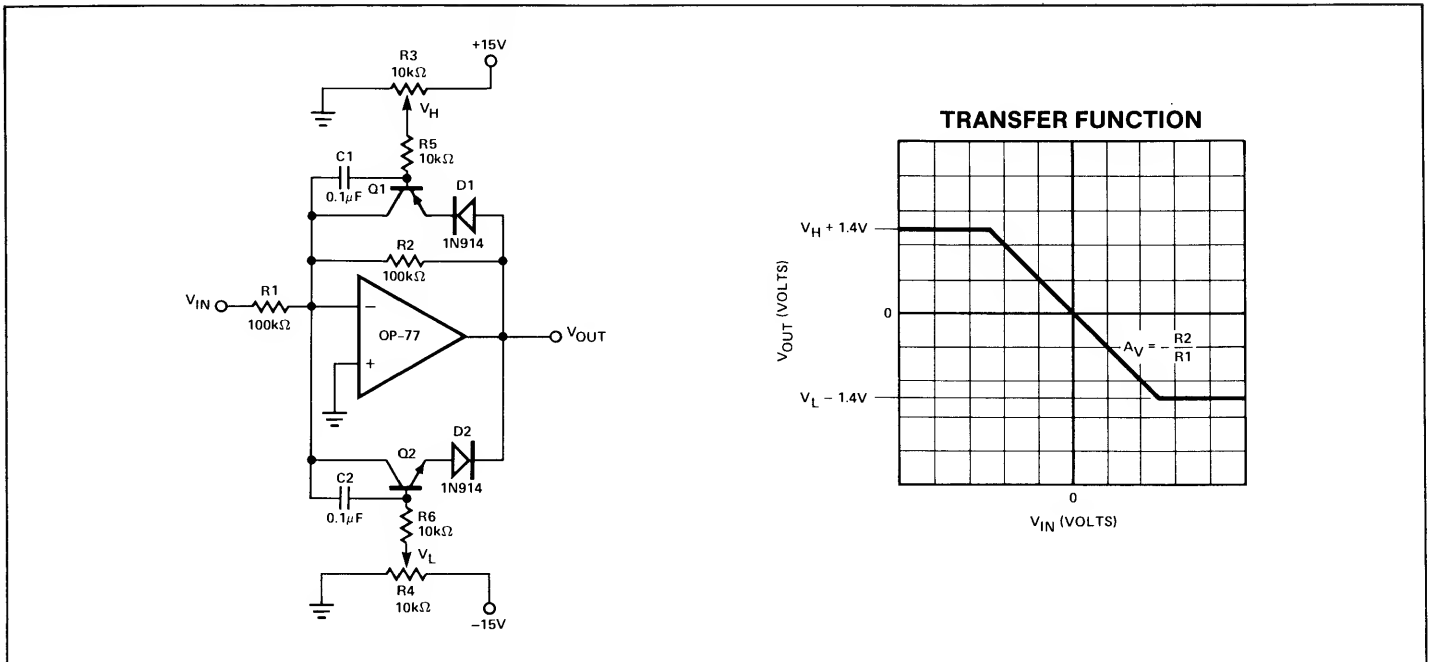
OP-77's high gain, high CMRR, and low TCV_{OS} assure high accuracy.

The circuit diagram illustrates a precision rectifier with a variable gain stage. The input signal V_{IN} (40mV - 4.1V_{p-p}, 65Hz) is applied to the non-inverting input of the first op-amp (A1, OP-27). The gain is controlled by a potentiometer (2N4856) connected to the inverting input of A1. The output of A1 is connected to the non-inverting input of the second op-amp (A2, 1/2 OP-227). The output of A2 is connected to the non-inverting input of the third op-amp (A3, 1/2 OP-227). The output of A3 is connected to the output of the circuit, V_{OUT} (0.2V_{p-p}, 65Hz). The circuit includes several resistors (R1, R2, R3, R4, R5, R6, R7, R8, R9, R10, R11) and capacitors (C1, C2) for signal conditioning and stability. Diodes D1, D2, D3, and D4 are used for precision rectification. The circuit is powered by a +15V supply and a -15V supply.

V_{OUT} exceeds 0.2V, V_{SM} becomes positive and drives the JFET gate negative. This increases the JFET's channel resistance lowering the gain of the A1. The reverse of this occurs if V_{OUT} falls below 0.2V peak-to-peak.

The values of C1 and C2 are chosen to optimize the circuits response time for a given input voltage frequency. This example was designed for a 65Hz signal. Higher frequencies would justify lower values for C1 and C2 to speed the AGC response.

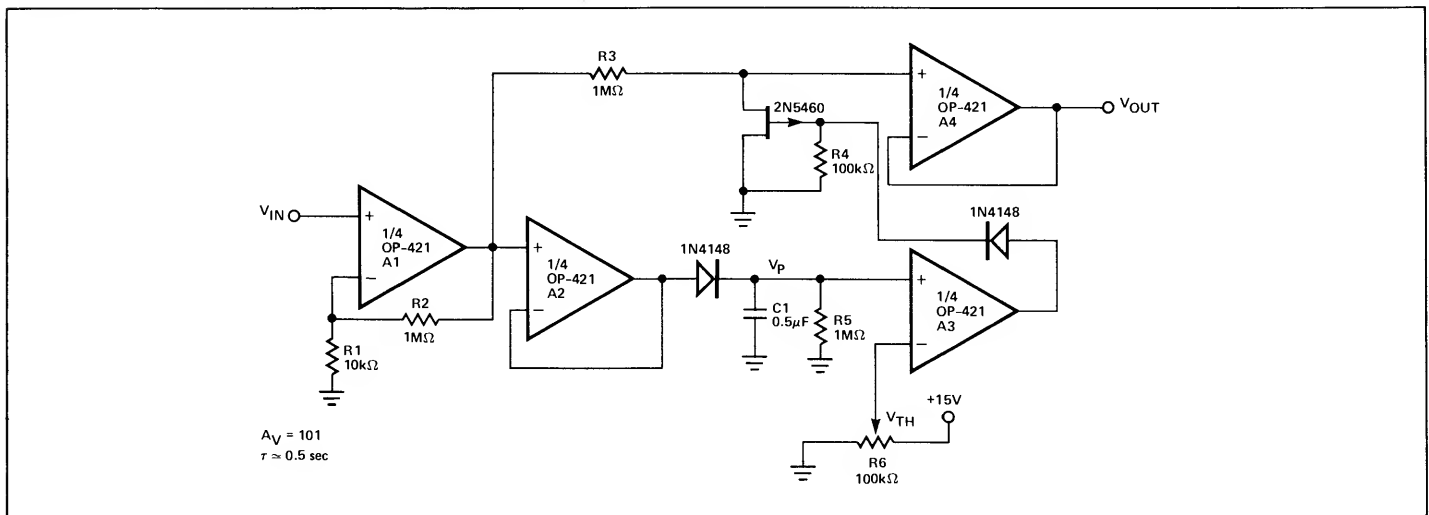
FIGURE 37: Amplifier with Active Output Clipping



This configuration allows adjustment of the op amp's maximum output voltage. Below the clipping levels, circuit gain is $A_V = -R2/R1$. As V_{OUT} rises above $(V_H + 1.4V)$, the base/emitter

of $Q1$ becomes forward biased, allowing collector current to flow to the summing node, thus clamping V_{OUT} . A similar action occurs as V_{OUT} goes below $(V_L - 1.4V)$ and is clamped by $Q2$.

FIGURE 38: Low Power Amplifier With Squelch



The OP-421 is the heart of this variable squelch amplifier which requires less than 2mA of supply current ($R_L = \infty$). A1 provides a high impedance input amplifier with $A_V = 1 + R2/R1$. Its output drives a unity gain output buffer, A4, and a peak detector with a time constant set by $C1$ and $R5$. When the output of the peak

detector, V_P , exceeds the adjustable threshold, V_{TH} , the comparator, A3, drives the gate of the P-channel FET high, turning it OFF. At lower input signal levels, V_P falls below V_{TH} , and the FET turns ON, clamping the input of A4 to ground.